Unprecedented participation of a four-coordinate hydrogen atom in the cubane core of lithium and sodium phenolates†

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Methalation of an ammonium tris(phenol) ligand affords new lithium/sodium derivatives having central pseudocubane motifs in which one of the metallic positions is replaced by a four-coordinate hydrogen atom.

Periodic trends in the chemical properties of elements are one of the most important and better established concepts in chemistry. They are elegantly represented in the Periodic table, which provides a visual representation of the connection between atomic number, electronic structure and group relationships. One of the best examples of group trends is found for the alkali metals which exhibit well-defined changes in their atomic properties. However, the position of hydrogen as the first element of Group 1 is a question which is still open to debate. Undoubtedly, the similarity of the electronic structure of H (1s1) with that of the alkaline elements (ns1) is not, at least obviously, translated into a similarity in the properties of these elements (i.e. under ambient conditions the former is a diatomic gas and the latter are solid metals). In spite of this, over the years a close relationship between hydrogen and the alkali metals rarely, if ever, been observed to exhibit well-defined changes in their atomic properties. However, the position of hydrogen as the first element of Group 1 is a question which is still open to debate. One of the best examples of group trends is found for the alkali metals which exhibit well-defined changes in their atomic properties. However, the position of hydrogen as the first element of Group 1 is a question which is still open to debate. One of the best examples of group trends is found for the alkali metals which exhibit well-defined changes in their atomic properties.

One answer to this question lies in the difference in size which leads to very different structural preferences (Chart 1). Thus, the smaller H atom, when covalently bonded to an electronegative atom, has a strong preference for a nearly linear two-centre secondary interaction with another electronegative centre. Higher coordination numbers are possible via additional secondary interactions, although the occurrence of three-centre hydrogen bonds (bifurcated) is less common and four-centre (trifurcated) hydrogen bonds are rarely observed in organic crystals (Chart 1). By comparison, heavier Group 1 elements are larger atoms which can easily accommodate higher coordination numbers and they almost exclusively participate in three and four-centre interactions via either association (oligomers), coordination of neutral donor ligands (solvation) or commonly by a combination of both (Chart 1). As a result, one of the most common structural motifs for these elements is the solvated pseudocubane.

In order to induce a structural equivalence of H and the alkali metals, one approach might be using a ligand framework combining the preference for association into the pseudocubane structural motif with the ability to force H into a trifurcated bonding mode. Overcoming the fundamental structural differences in this way would provide the opportunity for H to participate in a molecular metallic array typical of the alkali metals (behaving as an alkali metal structurally). As part of our studies of metal complexes of hydrogen, we have demonstrated that a four-coordinate hydrogen atom can participate in secondary interactions to a degree that is unprecedented.

Given these similarities, as well as recent advances in synthetic methodology, and the plethora of organic and metal–organic crystal structure data available, an obvious question to ask is why have hydrogen and the alkali metals rarely, if ever, been observed to perform the same structural role in a molecular crystal structure?

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triphenolamines (Scheme 1),9 here we report the synthesis and
caracterisation of multi-lithiated and multi-sodiated derivatives of
these ligands which display some unique structural features. This
includes the first examples of complexes in which a H atom partici-
pates in the pseudocubane motif typical of Li/Na aryloxides8,10 by
replacing one of the metallic positions, proving for the first time that
a structural equivalence between these elements is indeed possible.

The neutral tris(phenol) ligand 1 (Scheme 1) is readily prepared in
high yield following protocols provided in the literature.11 Addition
of one equivalent of an acidic enough phenol, such as pentachloro-
phenol (HOAr Cl), to acetonitrile solutions of

\[ \text{[H}_2\text{L]} \text{OArCl} \]

2, as a white solid in quantitative yield. Ligand 2 has
been characterized by comparing its NMR data with that available for
the crystallographically characterized chloride salt [H4L]Cl.12 A com-
mon feature of these two salts is the appearance of highly deshielded
resonances in their \(^1\text{H}\) NMR spectra \[ 9.28 \text{ (Cl)} \] vs. \[ 9.32 \text{ (P)} \],
corresponding to the N–H group, a feature which remains unaltered
in the metallated derivatives of 2 as discussed later on.

We then turned our attention to the synthesis of alkali metal
derivatives of these two ligands. Although the tri(lithium) and
tri(sodium) derivatives of 1 have recently been prepared and used
in situ as starting materials for the preparation of a variety of
transition-metal derivatives of 1,13 no structural characterization
has been reported so far for these compounds. The synthesis of
these complexes was achieved by addition of three equivalents of

\[ \text{^2\text{BuLi}} \text{ or NaHMDS (HMDS = N(SiMe}_3)_2] \]
to THF (Li) or Et2O (Na) solutions of 1, thereby yielding the trimetallated derivatives,

\[ [\text{M}_3(\text{S})_3\text{L}_3], \text{M} = \text{Li, S = THF (3)}; \text{M} = \text{Na, S = Et}_2\text{O (4)} \] (Scheme 1),
in good yields. X-ray quality crystals of both compounds were
obtained from such solutions on cooling (see ESI†).

The molecular structures of complexes 3 and 4 (ESI† and Fig. 1)
consist of a distorted face sharing double cubane. Corner-positioned
metals are coordinated with three μ3-O atoms and a solvent mole-
cule, completing the archetypal slightly distorted tetrahedral geo-
metry around them \[ \text{angles O–M}_3–\text{O} 91.3–132.1^\circ \] (3), \[ 88.1–143.7^\circ \] (4). In
contrast, the metal atoms belonging to the shared face are five-
coordinate, with two M–(μ3-O), two M–(μ2-O) and one M–N linkages,
defining a square pyramidal geometry with a sum of basal plane
angles of 358.9 \(^\circ \) (3), av. 360.2 \(^\circ \), and a range of basal to apical
angles of 91.5–95.7 \(^\circ \) (3) and 79.0–97.8 \(^\circ \) (4). The corresponding M–O
and M–N lengths in complexes 3 and 4 are unequivalent, in fact
quite similar to those previously reported for related Li14 or Na15
phenoxide cubanes (M–O), or amine bis(phenolate) complexes
(M–N).15 However, both compounds display one significantly
elongated M–O bond, \[ 2.227(5) \text{ Å (Li}_3–\text{O}) \] and \[ 2.530(3) \text{ Å (Na}_8–\text{O}), \]
with these figures being approximately 0.2 and 0.15 Å longer than those
typically found in other aryloxide cubanes.14,15 Such an effect might
be imposed by the rigid nature of the arms in the tris(phenolate)
ligands. Moreover, the corner-positioned metals in these two com-
plexes are further stabilized by the presence of short M–C(ipso)
and M–CH3 intramolecular interactions, which are similar to those
previously found by us for simple Li and Na aryloxide complexes
supported by polyamine ligands.16 Incidentally, complex 3 seems to
be the first lithium phenolate complex displaying a face-sharing
double cubane structural motif to be crystallographically characteri-
fied. Finally, the available NMR data for complexes 3 and 4 are
essentially consistent with the solid-state structures, but support
the presence of fluxional processes in solution which exchange the
environments of the metals and hydrocarbon chains through open
structures (see ESI†).

Keeping in mind that the ligand framework provided by the
amine(trisphenol) is flexible enough to accommodate Li and Na
cubanes, we turned our attention to the more challenging metalla-
tion of the protonated ligand \[ ^2\text{BuLi} \] or NaHMDS which.

In the solid state, complexes 5 and 6 (Fig. 2 and ESI†) display a
zwitterionic ammonium phenolate ligand of approximate

\[ \text{C}_3\text{ symmetry and geometry similar to those previously found in the}
structures of metal derivatives.3a,19 The M–O distances within
these complexes are only marginally shorter than those found for
3 and 4, probably reflecting a less constrained coordination of the
tris(phenolate) ligands. The triangle formed by the three metals is
capped by the \( 3\) μ-Oxygen atom of the OAr group, which is less
by tight bond. Each metal is further coordinated with one solvent
molecule completing a distorted tetrahedral geometry. In addi-
tion, we note the presence of short intramolecular M–Cl
interactions. In fact, the strongest of these interactions in 5
(Li3–Cl5 2.716(2) Å) is only slightly longer than that found for a
Li cation coordinated with a haloalkane (2.64 Å).20

More intriguing is the role of the central proton which is involved
in an unusual trifurcated NH–O3 hydrogen bond (mean H(1)–O
lengths 2.18 (5) and 2.32 (6) Å). Thus, the cores of these complexes
define a distorted cubane motif with the H atoms occupying one of

Scheme 1 Synthesis of new compounds.

Fig. 1 View of the molecular structure of 4 (30% probability) with hydrogens, methyl and ethyl groups omitted.
the corner positions (Fig. 3), and therefore effectively replacing one of the metal positions of a typical Li/Na aryloxide cubane. To the best of our knowledge, the structures of complexes 5 and 6 prove for the first time that a hydrogen atom is capable of replacing an alkali metal atom in a typical alkali metal structural motif. In fact, by comparing the cores of complexes 3-6 (Fig. 3) it is clear that the Li/Na to H replacement does not impose significant modifications of the cubane motifs.

Spectroscopic data obtained from solutions of crystalline samples of complexes 5 and 6 are consistent with the retention of “monomeric” cubane structural motifs found in the solid state, and with the pseudo C$_{3v}$-symmetry exhibited by the ligand framework (assuming free rotation for the OAc$^-$ group). Thus, the $^1$H NMR spectrum of 5 exhibits only one resonance ($\delta_{	ext{H}} = -0.89$ ppm), while the $^1$H NMR spectra of both complexes display just one set of signals for the aromatic protons of the equivalent phenolate rings, along with the expected AB multiplet for three equivalent methylenic (NCH$_3$) groups. The retention of the N–H bond in solution is clearly supported by the appearance of quite deshielded resonance ($\delta_{	ext{H}} = 12.7$ [5], 11.6 ppm [6]) values, which are even higher than that found for the free ligand 2, probably reflecting the existence of stronger NH···O$_3$ interactions in these metallated derivatives in solution.

In summary, we have reported for the first time the structural characterization of multi-metallated Group 1 derivatives of amine tris(phenolate) ligands, including the unprecedented participation of a metal-like hydrogen atom in the cubane core of an alkali metal (Li or Na) phenolate. We are now exploring the possibility of extending such a structural analogy to other related systems such as mixed-cubanes with different metals or anions.

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Notes and references

17. A preferential N–H deprotonation would be anticipated in view of the pK$_a$ values reported for related species [pK$_a$ = 9.80 (Me$_3$NH$^+$)], 10.86 (2,4,6-trimethylphenol).
18. For all the crystallizations yielded low-quality crystals which led to poor diffraction data. However, the crystallographic study allows for an unambiguous characterization of the structural motif.